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Modeling post-combustion CO_2 capture with amine solvents

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Abstract

Carbon capture and storage is a technology that can contribute to face the challenge of rising energy demand combined with a growing environmental awareness. In the present work, the CO_2 capture process with monoethanolamine (MEA) is modeled using the simulation tool Aspen Plus. Two different modeling approaches are studied and compared: the equilibrium and the rate-based approaches. An optimization of key process parameters is performed and process modifications are studied with the objective of improving the global process energy efficiency.

Keywords: CO_2 Capture, reactive absorption, process optimization, amine solvent degradation.

1. Introduction

One of the biggest challenges our modern society has to face is the preservation of the environment combined with the expectation of the world population to reach a higher standard of living, implicitly increasing the demand for energy. It is then necessary to improve our way of dealing with energy by diminishing energy wastes, promoting renewable energies, and reducing the impact of energy demand on the environment. This last point can be accomplished by reducing the amount of emitted greenhouse gases, especially CO_2 which is the most widely produced greenhouse gas.
Carbon Capture and Storage (CCS) applied on coal-fired power plants appears then as a necessary contribution to greenhouse gas mitigation in coal power plants, together with biomass co-combustion and efficiency improvement. According to the World Energy Outlook 2010 [1], by 2035, power generation from coal plants fitted with CCS exceeds that from coal plants not equipped with this technology.

Among different CCS technologies, the post-combustion CO_2 absorption in amine solvent and subsequent amine regeneration is one of the most developed capture technologies, so that the first large-scale equipped plants shall start running by 2015. One main drawback of this technology is the high energy requirement for solvent regeneration. In the present work, the post-combustion CO_2 capture process is simulated and optimized in order to explore ways for decreasing the process energy requirement.

2. Modeling approaches

Lawal et al. [2] consider different modeling approaches for modeling the absorber and stripper columns in the carbon capture flowsheet. Based on different assumptions for mass transfer phenomena and chemical reactions (CO_2 absorption and electrolyte dissociation reactions), two modeling approaches have been studied and compared in this work. Pressure drops in the columns have been set to 0.1 bar in the absorber and 0.3

bar in the stripper, neglecting variations due to process modifications. Activity coefficients, enthalpies and other thermodynamical properties are estimated with an electrolyte-NRTL model. The set of chemical equilibrium constants has been retrieved from the literature (Abu Zahra et al., [3]; Aspentech support 2010). The treated flue gas has a flow rate of 2500 Nm^3/h and a CO_2 content of 12vol-%. The solvent used for the simulation is an aqueous solution of 30-wt% monoethanolamine (MEA).

2.1. Equilibrium-based model

In the equilibrium-based model named Radfrac block model in Aspen Plus, each theoretical stage of the mass transfer columns is at a state of thermodynamic and chemical equilibrium. This model neglects the chemical reactions kinetics as well as the mass transfer limitations. It has been decided to model the absorber with four equilibrium stages and the stripper with six stages, which is a compromise between model precision and calculation complexity since it was not possible to reach convergence with more than five equilibrium stages in the absorber. A washing section has been added after each column. In the case of the absorber, a washing column made of 2 equilibrium stages performs the washing. In the case of the stripper, it was easier from a computational point of view to model the washing section by adding two washing stages inside the stripper column.

2.2. Rate-based model

In this second modeling approach, mass transfer limitations inside the column internals have been taken into account, as well as chemical reaction kinetics. The rate-based simulation has been performed in Aspen Plus using the RateSep block model with an electrolyte-NRTL model. In Table 1, parameters for the description of mass transfer phenomena have been chosen based on the literature (Abu Zahra et al., [3]; Zhang et al., [5]). Packing data are from the Esbjerg pilot plant (Knudsen et al., [4]).

Table 1. Rate-based model parameters

Parameter	Absorber	Stripper
Packing	IMTP50, Norton, Metal	IMTP50, Norton, Metal
Packing height	17m	13m
Section diameter	1.1m	1.1m
Reaction condition factor	0.5	0.5
Film discretization ratio	2	2
Film resistance	Liquid Discrxn (Liquid film discretization)/Vapor: Film	Liquid Discrxn (Liquid film discretization)/Vapor: Film
Interfacial area factor	2	1.5
Flow model	Mixed	Mixed
Discretization points for liquid film	5	5

As for the equilibrium model, the number of column stages is a compromise between calculation complexity and model precision. There are 17 stages in the absorber while the stripper has been modeled with 23 stages, inclusive 3 stages of washing section. The absorber washing section is modeled as an external column with 2 equilibrium stages.

3. Simulation results

Different methods are envisaged to decrease the process energy requirement. In this work, we first perform an optimization of key process parameters without modifying the process flowsheet. The studied parameter is varied while other parameters are kept constant and the energy requirement for solvent regeneration is used as a comparison criterion.

Then, two process modifications that require additional equipment are studied and compared based on the regeneration energy requirement. For each case, equilibrium and rate-based modeling approaches have been performed and compared. The capture rate has been fixed to a removal rate of 90% of the CO_2 present in the flue gas stream.

3.1. Process optimization

Among the parameters studied, three parameters have been identified as having the largest influence on the process efficiency: the stripper pressure, the solvent concentration and the solvent flow rate. Table 2 summarizes the parameter optimization. For each case, the base-case and the best-case value are indicated, as well as the reduction of solvent regeneration energy that has been achieved.

Table 2. Optimization of process parameters

	Stripper pressure	Solvent concentration	Solvent flow rate
Equilibrium model			
Basecase value	1.2 bar	30 wt-%	15 m³/h
Optimum value	2.2 bar	37 wt-%	13.9 m³/h
Regeneration energy	-11.6%	-8.2%	-1.6%
Rate-based model			
Basecase value	1.2 bar	30 wt-%	15 m³/h
Optimum value	2.2 bar	37 wt-%	12.4 m³/h
Regeneration energy	-16.9%	-5.4%	-2.8%

When varying the stripper pressure from 1.2 up to 2.2 bar, the solvent needs much less energy to be regenerated since a higher operating pressure leads to a higher temperature at the stripper bottom which favors the CO_2 desorption. This can be observed on Figure 1 (a). The regeneration energy requirement is decreased by more than 10% regardless of the modeling approach.

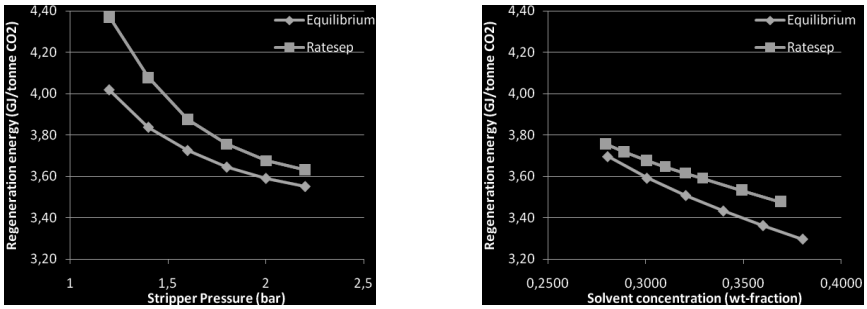

Figure 1: Influence of the stripper pressure (a) and of the solvent concentration (b) on the regeneration energy

When increasing the solvent concentration from 28 wt-% up to 37 wt-%, Figure 1 (b) shows that the amount of energy required for the solvent regeneration decreases quite linearly, but the slope of the curve depends on the modeling approach. However, the model doesn't account for degradation and corrosion problems that happen when the MEA concentration is increased.

Figure 2 shows that the regeneration energy reaches a minimum at a particular solvent flow rate. The lowest regeneration energy is observed at a flow rate value of 12.4m³/h in the rate-based model and of 12.8m³/h in the equilibrium model. The presence of a minimum in the regeneration energy requirement in function of the solvent flow rate has been observed and explained in previous experimental studies (Knudsen et al., [4]). From Figures 1 and 2, it can be observed that the minimum regeneration requirement is systematically lower in the equilibrium model. Since mass transfer and kinetics limitations are not considered in this modeling approach, the process efficiency is higher in this ideal case.

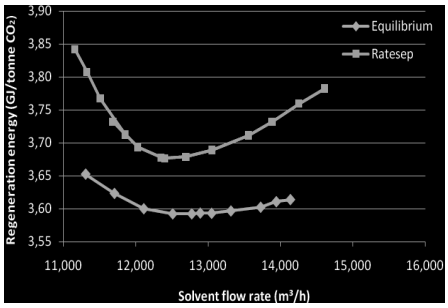

Figure 2: Optimization of the solvent flow rate

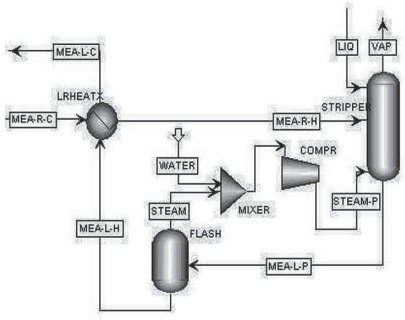

Figure 3: Flowsheet of the LVC

3.2. Process modifications

The first process modification studied is the lean vapor compression (LVC) which is shown in Figure 3. The goal of the modification is to partially evaporate the regenerated solvent at the stripper exit in order to recover energy under the form of vapor. This vapor generated in the adiabatic flash evaporator at lower pressure is then compressed and sent back to the stripper where it acts as stripping steam and induces a reduction of the reboiler duty. This requires the stripper to be operated at a pressure higher than atmospheric pressure. The simulation has been performed with the stripper being operated at 2 bar. Both modeling approaches have given similar results: thanks to this process modification, the regeneration energy requirement has been driven from 3.6 down to 2.9 GJ/t CO_2, which corresponds to a reduction of about 20%. Taking into account the energy supplied for compressing the lean vapor, the process exergy demand is globally reduced by 14% which is considerable. While varying the flash pressure, we observed that the lower the flash pressure, the higher the energy savings.

The second process modification discussed in this article is the absorber intercooling. By cooling the solvent flow between two absorber stages, the absorption is performed at a lower average temperature. Since the CO_2 absorption is an exothermic process, this modification improves the global process efficiency. The impact of the intercooler location has been studied in Figure 4 (a). The first point of each curve represents the

case with no intercooler and the last point the case with a flue gas precooler before the absorber.

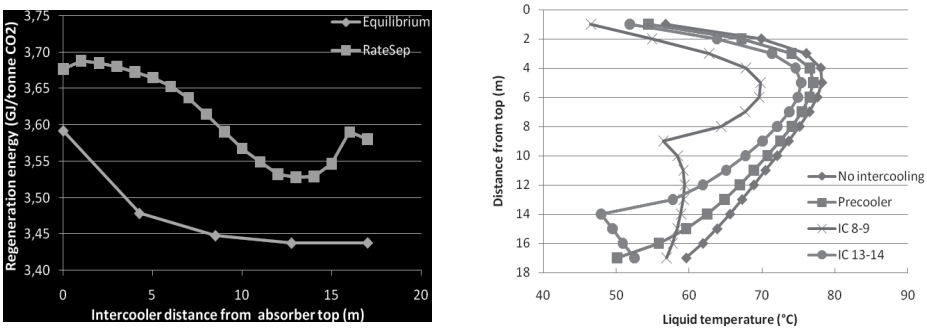

Figure 4 (a): Impact of the intercooler location on the regeneration energy requirement.
(b): Absorber temperature profiles for different intercooler locations

The lowest regeneration energy requirement is achieved when performing intercooling close to the column bottom. Since less approximations are made for modeling mass transfers inside the columns in the rate-based approach, column internals have been studied using the rate-based model. Absorber temperature profiles are presented on Figure 4 (b). Intercooler located between absorber stages 13 and 14 gave the best results in terms of global process efficiency, reducing the regeneration energy requirement by 4% in comparison to the case with no intercooling.

4. Conclusion

Two modeling approaches have been used for simulating the post-combustion CO_2 capture with amine solvent. A parameter optimization and two process modifications have been performed. Simulation results evidence the potential energy savings that can be achieved by optimizing key process parameters and improving the process flowsheet. Those results will be matched with experimental data from a 5000Nm³/h pilot plant in collaboration with the industrial partner Laborelec, member of the GDF-Suez group. Further research includes experimental studies on solvent degradation and a multi-objective optimization considering investment, energy cost and solvent replacement.

Acknowledgement

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